A Geological and Ecological Reconnaissance off Western Oahu, Hawaii, Principally by Means of the Research Submarine "Asherah"[1]

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ABSTRACT: In November 1965 a combined geological and ecological reconnaissance of the sea floor off western Oahu was undertaken using a variety of methods and techniques to maximize both the range and reliability of the information obtained. Bottom topography and fish concentrations were surveyed with a precision echo sound recorder for which the transducer was towed in a streamlined housing below the research ship. Photographic bottom surveys were also made with an automatic stereo-camera system, and some bottom dredging and trawling were undertaken to secure samples of the bottom and the biota. Direct visual observations were also made using a small research submarine largely in the depth range of 25–180 meters.

The dominant geological features were a series of submerged, wave cut, largely sand covered terraces separated by rocky escarpments. The major terraces were an upper one terminating seaward at approximately 60 meters, an intermediate one from 70 to 120 meters, and a deep one beginning from a shoreward depth of 180 meters or deeper.

Patterns of littoral sand movement were observed to be southerly in the region between Kaena Point and Kepuhi Point with a substantial movement offshore. It was estimated that approximately 10,000 cubic yards of calcareous sand move seaward and are deposited annually on the inner portions of the deep terrace.

Associated with the escarpments were large and discontinuous aggregations of fish and, on the upper and intermediate terraces, extensive beds of the clam *Pinna muricata*. The observed patterns of distributions may be a response to the localized accumulation of food. Organisms which make nocturnal vertical migrations in adjacent deep water may be swept shoreward by surface currents and become trapped on the terraces. The collection of planktonic organic material in the thermocline where the water increases rapidly in density with depth may be a mechanism for the localized accumulation of particulate food of value to the clams.

The simultaneous use of a variety of observational techniques in an area provided non-identical and independent observations of the same situations. This served to confirm the information obtained and to add new and significant detail.

During november of 1965 a reconnaissance of the sea floor geology and of the marine ecology off western Oahu, Hawaii was made using a remotely operated stereo-camera system, a precision echo sounding recorder, biologic and geologic dredges, and, most importantly, a two-man deep-diving research submersible vehicle. Surface support was supplied by the University of Hawaii's 90-ft research vessel, the "Teritu." The intent of the investigation was to make a series of direct observations of the geomorphology and the biota by means of the submersible vehicle and to correlate with these observations data collected at the same time and in the same area by means of conventional, indirect data-gathering techniques (submarine photography, biologic and geologic dredging, etc.). The experiments were successful: 15 deep dives were made with the research submarine, most to 180

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meters; 500 black and white and an equal number of color photographs were taken, some from the remote surface controlled stereo-camera, some from the submarine; 20 bathymetric profiles were run normal to the coast by the "Teritu" and numerous geological and biological specimens were collected from the terraces and escarpments by the various dredges and trawls. The following report summarizes these data and compares their relative merits for geological and biological reconnaissance surveys.

AREA OF INVESTIGATION

The area of investigation was chosen mainly with the intent of selecting oceanographic and meteorologic conditions that would be optimum for handling a small, research submarine. Since the submarine diving operations necessitated surface towing of the vehicle, and since the replenishment of compressed air, recharging of the battery bank, and maintenance required moving alongside the mother ship, a leeward coast was necessary. Secondary requirements in the selection of the area of investigation were connected with the land-based logistical support of the entire operation over a 10-day period.

Because of the prevailing easterly tradewinds and the resulting near permanency of a lee coast along western Oahu, it was possible to meet the above requirements in an area of intensely interesting submarine features and a poorly known biota. Consequently a 14-kilometer length of coast along western Oahu, from Kaena Point to Kepuhi Point, was chosen for the reconnaissance (Figs. 1 and 2). This area provided ideal lee operating conditions during November; it was within ½ hour by boat from Pokai Bay, a replenishment harbor just to the south; it was a single isolated geological unit or cell in regard to the littoral circulation of sand; and

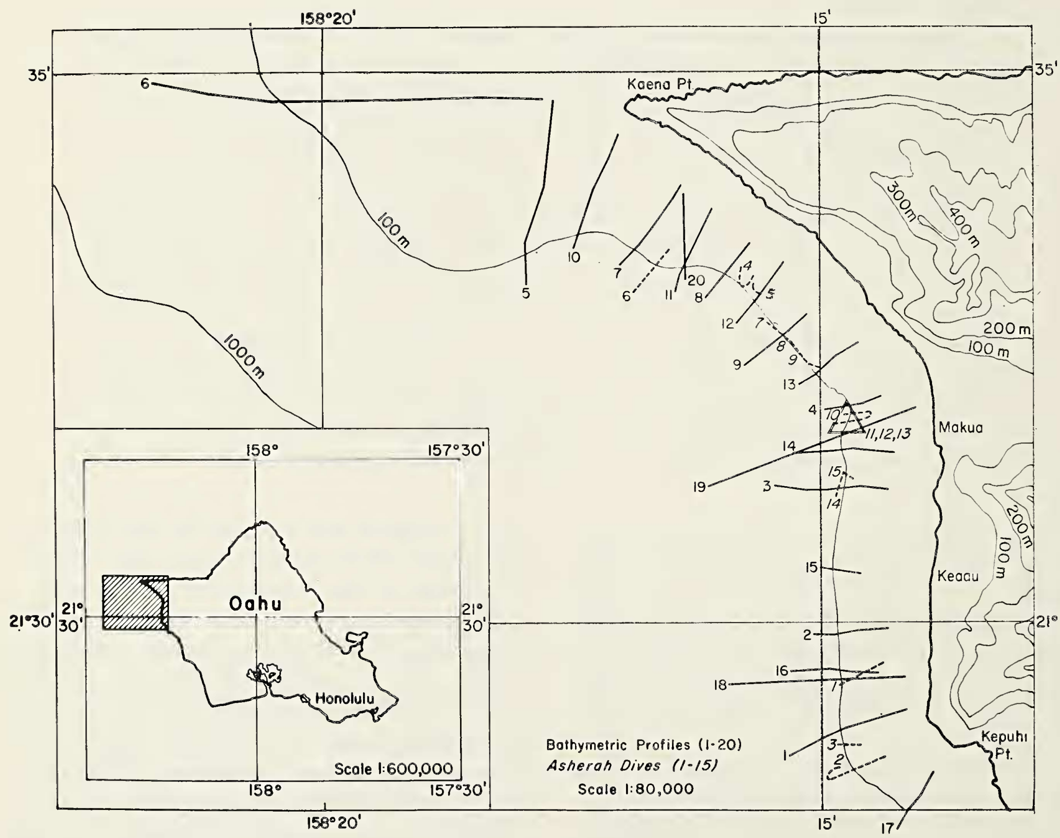

FIG. 1. Location chart.

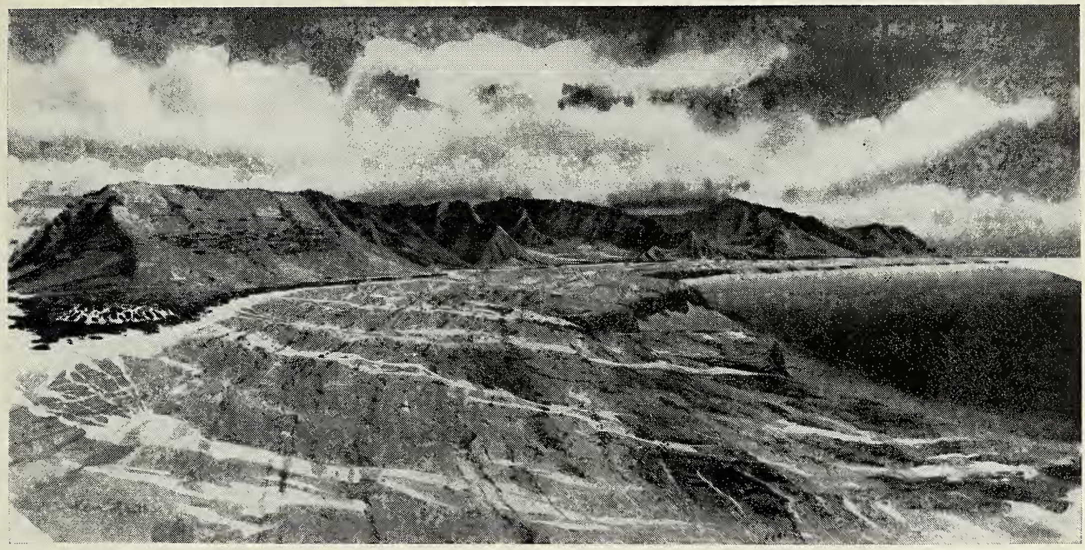

FIG. 2. View from above Kaena Point. The seafloor is delineated from the water's edge to and beyond the escarpment between the Mamala and Lualualei terraces. Sand channels and reef rock outcrops are shown. (Drawing by Ken Shutt.)

it contained numerous, well developed submarine terraces and escarpments that could be correlated with ancient stands of the sea, as recorded in recent borings made on the Ewa Plain 20 miles to the south.

ENVIRONMENTS

Oceanographic

SURFACE CURRENTS: The Hawaiian Islands are located on the northern edge of the Pacific North Equatorial Current, a westerly-flowing component of the large anticyclonic circulatory pattern that dominates the North Pacific Ocean. Within a few hundred miles of the Hawaiian Islands the surface currents all set toward the western quadrant, generally with a drift of about ½ knot. As this large mass of water flows past the Hawaiian Islands it breaks up on the downstream side of the islands into large, semi-permanent eddies, some cyclonic and others anticyclonic. Superimposed upon these eddies, and in some cases completely dominating the surface circulations, are strong tidal currents.

About 10 miles off western Oahu the surface water appears to consistently move south, in conformation with the general flow of water from the east through the Kauai Channel, and join the circulation of an anticyclonic eddy about 20 miles in diameter located about 20 miles directly offshore at southwest Oahu (Latham, 1967). The velocity of the near-Oahu portion of this eddy was measured by Latham and found to be about ½ knot to the south.

Nearer shore the surface currents have been found to reverse themselves semi-diurnally in accordance with the tides. During flood tides there is generally a flow of water to the south just west of Kaena Point, and to the southeast, south of the point. These currents have been measured at about 1½ knots (Latham, 1967). However, immediately adjacent to the coast, both north and south of Kaena Point, there is a persistent drift of water of 1–2 knots that follows the coastline to a convergence point some few miles west of Kaena Point. These northwest-setting currents are more intense during ebb tide and have been measured at a maximum of 5 knots (Laevastu et al., 1964).

During the diving operations with the "Asherah" a nearly constant set to the north and west was encountered. The drift of this current varied, but ½ knot was not uncommon even to depths of 180 meters.

WAVES: Wave energy reaching the western coast of Oahu can be approximately represented by four wave types related to predominant meteorological conditions within the Pacific Basin:

(1) *Kona Wind Waves:* Generated by local westerly storms; period 7 seconds, direction of approach SSW, height 2.4 meters, frequency of occurrence[3] 9.5%, generally during the winter months.

(2) *North Pacific Swell:* Generated by the passage of low pressure areas across the Northern Pacific Basin; period 13 seconds, direction of approach NNW, height 3.4 meters, frequency of occurrence 89%, generally during the winter months.

(3) *Southern Hemisphere Swell:* Generated by low pressure areas in the Southern Hemisphere; period 15 seconds, direction of approach S, height 0.9 meters, frequency of occurrence 53%, entirely during the summer months.

(4) *Tradewind Waves:* Generated by the easterly tradewinds; period 8 seconds, direction of approach E and NE, height 2.4 meters, frequency of occurrence nearly 100% but, due to the sheltering effect of Oahu, of minor importance in the area of investigation.

The currents that lie within the breaker zone, and which are of prime importance in the alongshore transport of littoral sand, are dependent upon the wave regime and consequently vary greatly in direction and speed. Waves from the northwest quadrant (generally North Pacific Swell) create southeastwardly flowing currents; waves approaching from the southwest quadrant (generally Southern Hemisphere Swell and Kona Wind Waves) produce currents flowing toward the northwest. Current speeds vary from less than 1/10 knot to about 1/2 knot.

THERMAL STRUCTURE: The island of Oahu centered at 21°30′ north latitude is in tropical water with a permanent surface isothermal layer. The long term (1936–1956) average temperatures within a 250-mile radius of Oahu are given in Table 1, together with the range for depths from the surface to 2000 meters.

It will be noted from Table 1 that the greatest range in temperature occurs between 200 and 300 meters. These are the depths where the thermocline is ordinarily found. However, the thermocline fluctuates in depth depending upon the stirring effects of the wind or lack thereof, and the depths through which it fluctuates will show a greater temperature range than depths above or below. A protected lee area such as the Waianae coast of Oahu, because of reduced strength of the prevailing tradewinds, may have a shallower mixed layer. During the "Asherah" dives in this area, the location of the thermocline was inferred by noting the depth at which both visual ranges were minimal and the greatest apparent concentration of particulate matter occurred. On this basis the thermocline was between 70 and 100 meters. No vertical temperature profiles were obtained at the time of the diving operations.

[3] Per cent of the year during which each wave type occurs.

TABLE 1

AVERAGE TEMPERATURE DATA FOR AN AREA WITHIN A 250-MILE RADIUS OF OAHU, HAWAII*

DEPTH IN METERS	TEMPERATURE (DEGREES C)	TEMPERATURE RANGE (DEGREES C) + OR —
0	24.6	2.2
50	24.1	2.5
100	22.3	2.3
200	16.7	4.7
300	12.4	3.7
500	8.2	2.7
800	4.8	0.6
1000	4.2	0.7
1500	2.8	0.2
2000	2.1	0.2

* From Dr. B. C. Heezen.

Geologic

The main Hawaiian islands lie toward the southeastern limit of the Hawaiian Ridge, a large, positive, geomorphic feature built up of shield-shaped basaltic domes along a 1,600-mile fissure in the north-central Pacific Ocean. Neither the age nor the geologic history of the Hawaiian Ridge is well known, but recent investigations have indicated a Tertiary age for most of the Ridge, with a developmental sequence starting in the northwest and proceeding to the southeast. The growth of the Ridge has been accompanied by large scale subsidence; superimposed upon this subsidence have been major Tertiary and Quaternary eustatic sea level fluctuations due to tectonic deformation of the Pacific Basin and intense continental glaciation. The result of these positive and negative shifts of sea level has been the formation of numerous marine terraces, reef horizons, and beaches, now found at various positions from several thousands of feet below to several hundreds of feet above the present sea level.

Oahu, the center of population and site of the present investigations, is the third largest of the Hawaiian Islands with an area of 604 square miles. The island was built up above sea level by the emergence and coalescing of two large volcanoes, the Koolau Volcano on the east and the Waianae Volcano on the west. Today the remnants of these two volcanoes form the Koolau and Waianae mountain ranges respectively, between which lies the Schofield Plateau, a flat, low plateau consisting of alluvious and thinly-bedded lava flows. On the north and south flank of the island are wide coastal plains.

Along western Oahu, the geology is completely dominated by the deeply eroded remnants of the Waianae Volcano. The center of volcanic activity of this volcano was a caldera near Kolekole Pass at the head of Lualualei Valley. From this caldera and from the rift zones extending from it, large amounts of fluid lava were extruded over many millions of years. The older extrusions were thin, fluid, pahoehoe flows; the later flows were massive, adesitic aa.

The main extrusive activity of the Waianae Volcano terminated several millions of years ago; the cessation of major eruptions was followed by deep erosion of the volcano and later by a few secondary eruptions of small magnitude near the caldera. During the initial period of erosion the major valleys were formed; some, such as Lualualei, were graded to stands of the sea over 600 meters below the present sea level. With subsequent and continued subsidence of Oahu these major valleys were drowned, and eventually thick sections of reef, lagoonal, and beach sediments were deposited.

The present geomorphology of the western coast of Oahu is dominated by the deeply eroded valleys described above. Between these valleys, sharp spurs extend down to the sea and offshore as submarine ridges. These spurs and their offshore extensions act as effective barriers to the alongshore transport of nearshore sand and other sediment. Consequently the nearshore environment is divided into littoral units or cells between which little exchange of sand occurs, and within which the amount of sand produced is in equilibrium with the amount of sediment lost from the cell. Contributions of littoral sand are from coastal streams and from the disintegration of calcium carbonate skeletal remains on the reef flats; losses of littoral sand are by offshore sedimentation into deep water, and to a lesser extent by paralic deposition and by the landward migration of beach dunes.

The coastal zone between Kaena and Kepuhi points, the area of the present study, is essentially one large littoral cell; there appears to be very little nearshore sand transport around either point. The cell is dominated by the large Makua Valley located in the center of the cell; the major reservoir of beach sand is located at the mouth of this valley. Above sea level there are probably no fewer than four well-developed ancient sea level stands preserved, the most pronounced at +8 meters. Below sea level there are at least five additionally preserved sea level stands, at —18, —55, —90, —550, and —1100 meters (Stearns, 1966:23).

Biologic

The nature of the sea floor in the area of investigation has been described elsewhere. As an environment it is a series of sand-covered terraces paralleling the trend of the coast and backed by discontinuous escarpments. In places, the sand covering on the terraces is thin and the epifauna scant, even where the rock is bare due possibly to sand scouring. This is most apparent in shallow water from 10 to 30 meters in depth. In depths of 30 meters or less there are some areas with a vigorous growth of hermatypic corals. There are extensive beds of the clam *Pinna muricata* on the sand-covered terraces in depths between 35 and 100 meters, and occasionally on rocky areas numerous vasiform coral colonies, possibly a *Montipora,* are found in 60 to 80 meters of water.

The sand-covered terraces, other than areas of *Pinna* beds, have little apparent life. Some dredging on the terraces resulted in the collection of numerous heart urchins *Brissus latecarinatus*. There were also very few fishes over the terraces. The escarpments had in general an abundant fauna of fishes and invertebrates.

Areas of some of the terraces have a scattered covering of rubble with attached algae as deep as 90 meters. Algae also were noted on the escarpment areas. Where the escarpment was deeper than 90 meters it appeared to lack algal growth and had a poorer epifauna as compared with the escarpments in shallower water. At all depths, in holes and small caves, an abundant fauna was noted of fishes and invertebrates characteristic of their environment.

RECONNAISSANCE TECHNIQUES

"Asherah" Operations

To obtain the maximum amount and the highest quality of scientific data during the investigations it was felt that, simultaneously with the use of the "Asherah," other techniques should be employed to measure biologic and geologic parameters. Consequently, while the "Asherah" was diving, the "Teritu" was engaged in bathymetric or photographic surveys or geologic and biologic dredging operations in the same general area. (For equipment specifications see the APPENDIX.)

The "Asherah" was moored each night alongside the "Teritu" off Makua Valley. During the night her batteries and compressed air tanks were recharged. The daily procedure was to take the "Asherah" in tow with a 16-foot power boat early each morning and proceed to the proposed diving locality. Upon reaching the diving site the "Asherah" was released, made ready for diving, and boarded. Each dive lasted for from 2 to 3 hours and generally two dives were made a day. During the time the "Asherah" was actually under water she was accompanied on the surface by a 13-foot power boat with which she maintained direct and continual communications. From November 1 through November 5, 15 dives were made.

Remotely Controlled Stereo-Photography

While the "Asherah" and her accompanying small boats were actually engaged in diving operations, the "Teritu" was also employed in data collection. Each area transversed underwater by the "Asherah," as well as additional interesting areas, were photographed from the surface by the "Teritu." Edgerton, Germeshansen and Grier cameras were used, depth-controlled by a pinger unit mounted on the camera frame and monitored by the Precision Echo Sonic Recorder aboard the "Teritu." A stereo- (double-)camera arrangement was employed, and both black and white and color film were used. In all, 500 pairs of photographs were taken at depths of 120 to 300 meters.

Echo Sounding

Numerous continuous echo sounding profiles were made by the "Teritu" prior to, during, and subsequent to the "Asherah" dives. The equipment used consisted of an EDO echo sounder towed outboard in a Braincon streamlined housing and a GIFFT recorder (Precision Echo Sonic Recorder). Because of the high degree of sensitivity of the recording unit, it was possible to record fish schools and micro-relief on the various submerged terraces, and consequently the echo sounding profiles were instrumental in determining the diving localities for the "Asherah." Twenty of the best echo sounding profiles are shown in Figures 3a–3d, their localities in Figure 1; these records form the basis for the bathymetric chart shown in Figure 4. Three of the echo sounding profiles (Nos. 4, 10, and 11) show excellent examples of fish populations, and consequently are reproduced in Figures 5, 6, and 7.

Geologic Dredging

Numerous attempts to dredge rock from the various marine terraces and escarpments were made by the "Teritu." Heavy pipe dredges with chain bridles were used connected to the ship by ⅜-inch steel wire, but the light "A" frame and sheeving system of the "Teritu" prevented heavy strains being put on the system. Dredging on the outer edge of the Penguin Banks Shelf, just north of Kepuhi Point, recovered reef rock fragments with freshly broken surfaces. These samples came from depths of from 50 to 60 meters and probably represent the outcrops marking the boundary between the Penguin Banks and Mamala shelves. Similar reef rock fragments were obtained at depths of 120 meters on the Mamala Shelf off Makua Valley.

Attempts to break rock off the major escarpment between the Mamala and Lualualei shelves

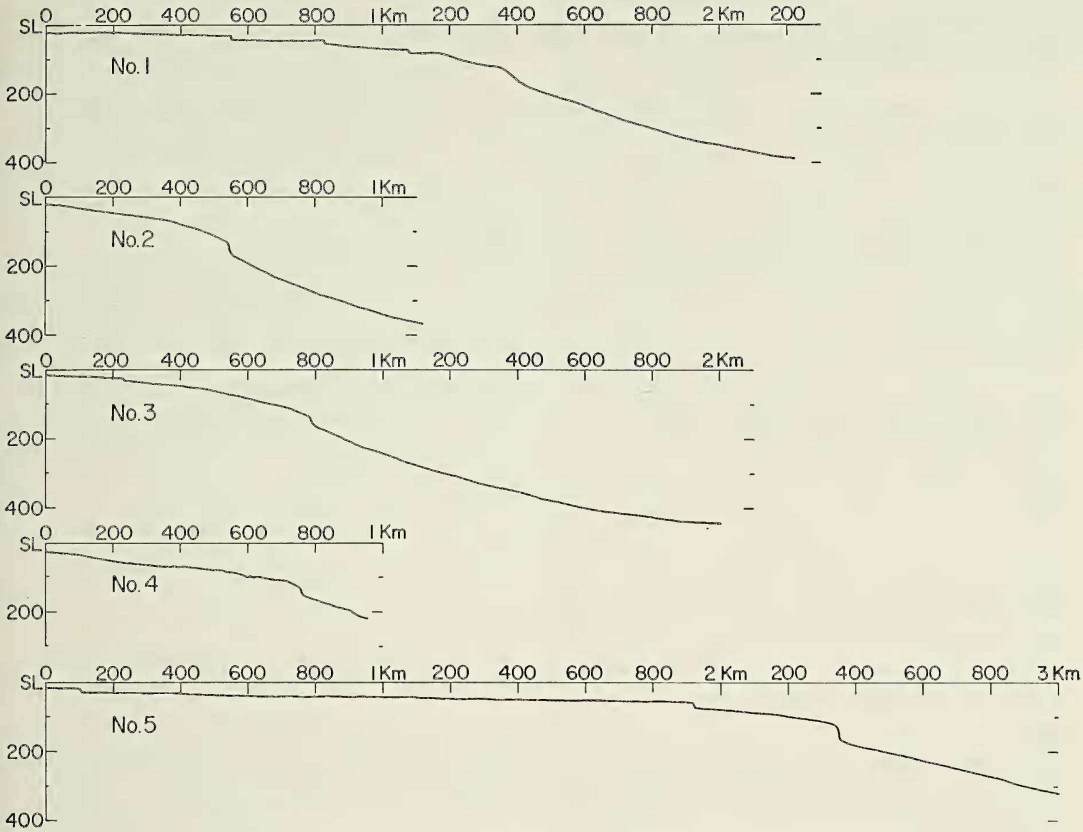

FIG. 3a. Bathymetric profiles Nos. 1–5. See Figure 1 for locations.

met with failure. In each case the ship had to be backed to recover the dredges and the cutting edge of the dredge was frequently bent.

Trawling

A standard shrimp try trawl was tested as a collecting device in the general area of the "Asherah" operations, but deeper and south of the area off Pokai Bay. The trawl was hauled twice in about 350 meters of water and took a scant catch with a good deal of damage to the net. The echo sounding record had indicated a smooth bottom. The tension on the cable reached one ton, overloading the ship's generator. A new net was rigged and shot in a sand channel off Pokai Bay which was presumed to be free of obstructions. The gear was towed perpendicularly to the trend of the coast offshore beginning in 20 meters of water and ending in about twice that depth. A large catch was taken of nearshore fishes, including a female *Dasyatis hawaiiensis* whose weight must have exceeded 100 kilograms even though the fishing time was quite short. Again the net was badly damaged.

Both the dredging and trawling operations indicated that the "Teritu" was quite inadequate for this use.

MARINE GEOLOGY

Geomorphology

The submarine geomorphology between Kaena and Kepuhi points, is dominated by a series of marine terraces separated by escarpments. From the "Asherah" it was possible to discern at least three distinct levels:

(1) An upper level terminating seaward at a depth of approximately 60 meters.

(2) An intermediate level extending from about 70 meters down to approximately 120 meters.

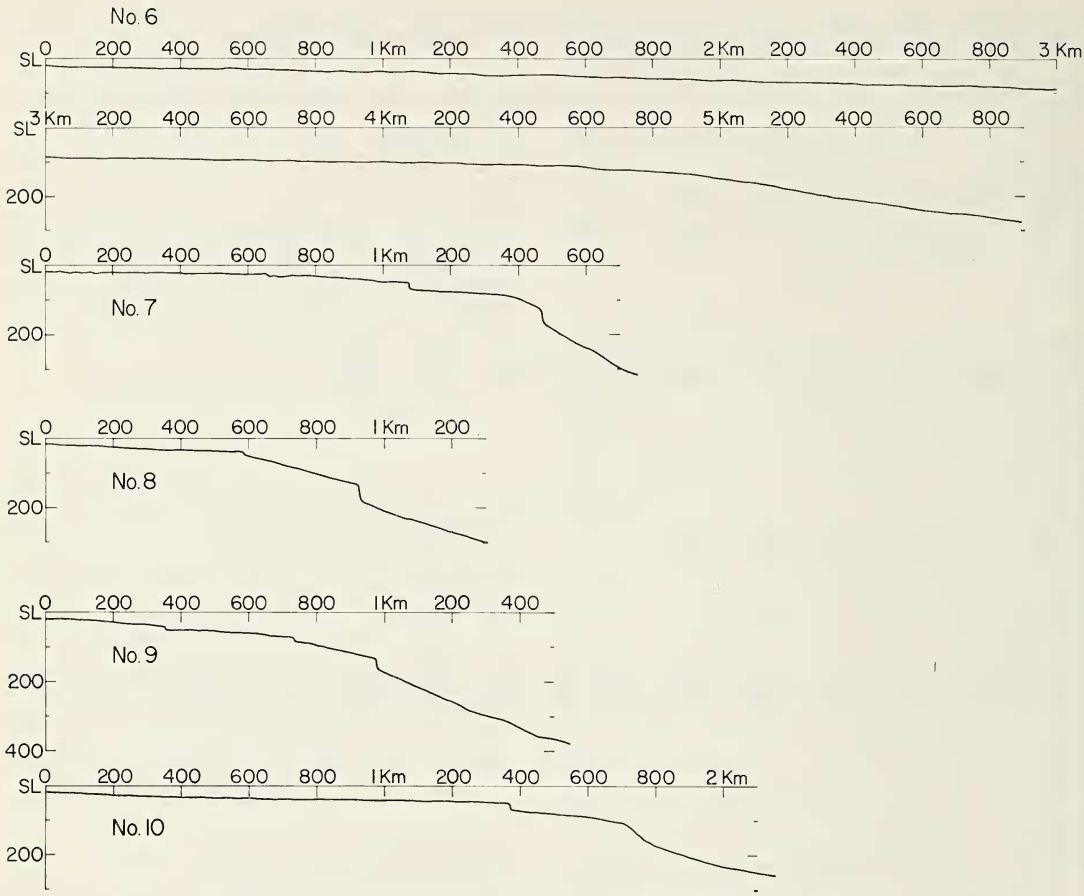

FIG. 3b. Bathymetric profiles Nos. 6–10. See Figure 1 for locations.

(3) A deep level extending from about the diving limitation of the "Asherah" (180 meters) seaward. These marine terraces observed from the "Asherah" correspond fairly well with the submarine terraces recorded by Ruhe et al. (1964) in their careful analysis of the shorelines and submarine terraces of Oahu. It is known from work done by Stearns (1966) and by Ruhe et al. (1964) that a shoaler terrace also exists in the depth range of 5–18 meters, but this terrace was above the general working range of the "Asherah" during the present investigation.

It is not the purpose of this paper to attempt to refine on the depth limitations computed by Ruhe for each of the submarine terraces around Oahu. Interested readers should refer to his work cited above or to several of H. T. Stearns' works on the same subject. However, it is our purpose to describe certain features of these terraces that lay beyond the ability of these earlier workers because of the previous lack of means for direct visual observation.

The most striking feature of the submarine geomorphology off northwestern Oahu as observed by the "Asherah" was the escarpment between the lower and intermediate terrace levels (here equated to the Lualualei and Mamala shelves, 247–932 meters and 75–124 meters, respectively, of Ruhe et al., 1964). After viewing firsthand this major escarpment and the submarine terraces it separates, it seems no wonder that the depth determinations for the various shelves around Oahu have such a wide range: the near vertical nature of this escarpment prevents accurate determinations of its features by echo sounding, it is cut in many places by wide sand channels that grade gently

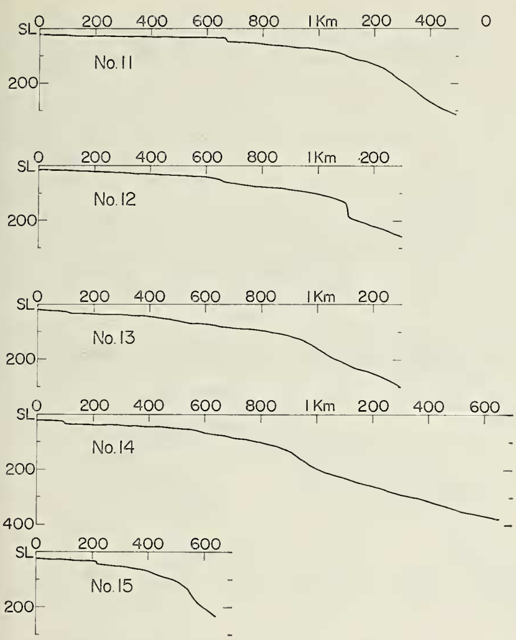

FIG. 3c. Bathymetric profiles Nos. 11–15. See Figure 1 for locations.

from one terrace to another, and the escarpment is almost completely burried by nearshore sand for almost one-half its length—from Makua Point to Kepuhi Point.

Figure 2 shows the relationship of this deeper escarpment to the upper terrace levels and generally to the land topography. Figure 9 shows a detailed picture at a point slightly north of Makua Valley. Generally this escarpment between the Lualualei and Mamala shelves is much more pronounced in the area north of Makua Valley. In places it is perfectly vertical for over 30 meters with caverns and indentations in the lower levels and in some localities large boulders at the base. The amount of sand in the offshore zone increases to the south (as explained in the section on Littoral Processes below), and this increase in offshore sand partially masks the base of this escarpment and, far to the south near Kepuhi Point, completely obliterates it. Starting at about Makua Valley, large spillways or canyons cut through the escarpment and, together with the sand spilling over the rim and fragments from the escarpment itself, form immense talus slopes (Fig. 9). On most of the dives directly to 180 meters the "Asherah" alighted on a 10°–15° talus slope which dropped off seaward into darkness and extended upward and shoreward to the base of steep cliffs or over broken outcrops of rock to the Mamala Shelf.

In the area of investigation it would be almost impossible to fix the depth of the inshore edge of the Lualualei Shelf by means of echo soundings: the sand and talus deposits are probably tens of feet in thickness and completely bury the inner portion of the shelf. Just south of Kaena Point, where the base of the escarpment is covered with large boulders, the depth is approximately 186 meters. These boulders most probably are the remnants of a boulder beach; together with the near vertical escarpment above them they possibly represent the strand line and sea cliffs for a very prolonged stand of the sea. The age of the Lualualei Shelf is not known, but its possibly warped and titled surface (Ruhe, 1964) and the recovery from it of a possible Miocene fauna (Menard, Allison, and Durham, 1962) would indicate mid-Tertiary. Irrespective of the absolute age, a long period of stability of the sea level is indicated by the massive nature of the escarpment observed from the "Asherah." A continuation of this escarpment can be traced around most of western and southern Oahu.

The upper edge of the escarpment described above terminated abruptly in a nearly horizontal marine terrace. The seaward or deeper edge of this terrace generally was encountered at depths of about 120 meters, but ranging from approximately 100 to 140 meters in depth. Landward the terrace continued for hundreds of meters, finally terminating against a very broken line of irregular outcrops. Figure 8 is a representation of this intermediate terrace (here referred to as the Mamala Shelf) at a depth of about 90 meters. The nature of the outcrops defining its inner edge is shown as well as some of the surface features of the shelf. The outcrops themselves were very interesting as many had large caves in their seaward sides and were 3 to 6 meters in height and perhaps twice that in diameter. A definite delineation of these outcrops, generally parallel to the shoreline, could be seen. A representation of this delineation is attempted in Figure 8.

It was possible to trace the Mamala Shelf landward in some areas to depths of less than

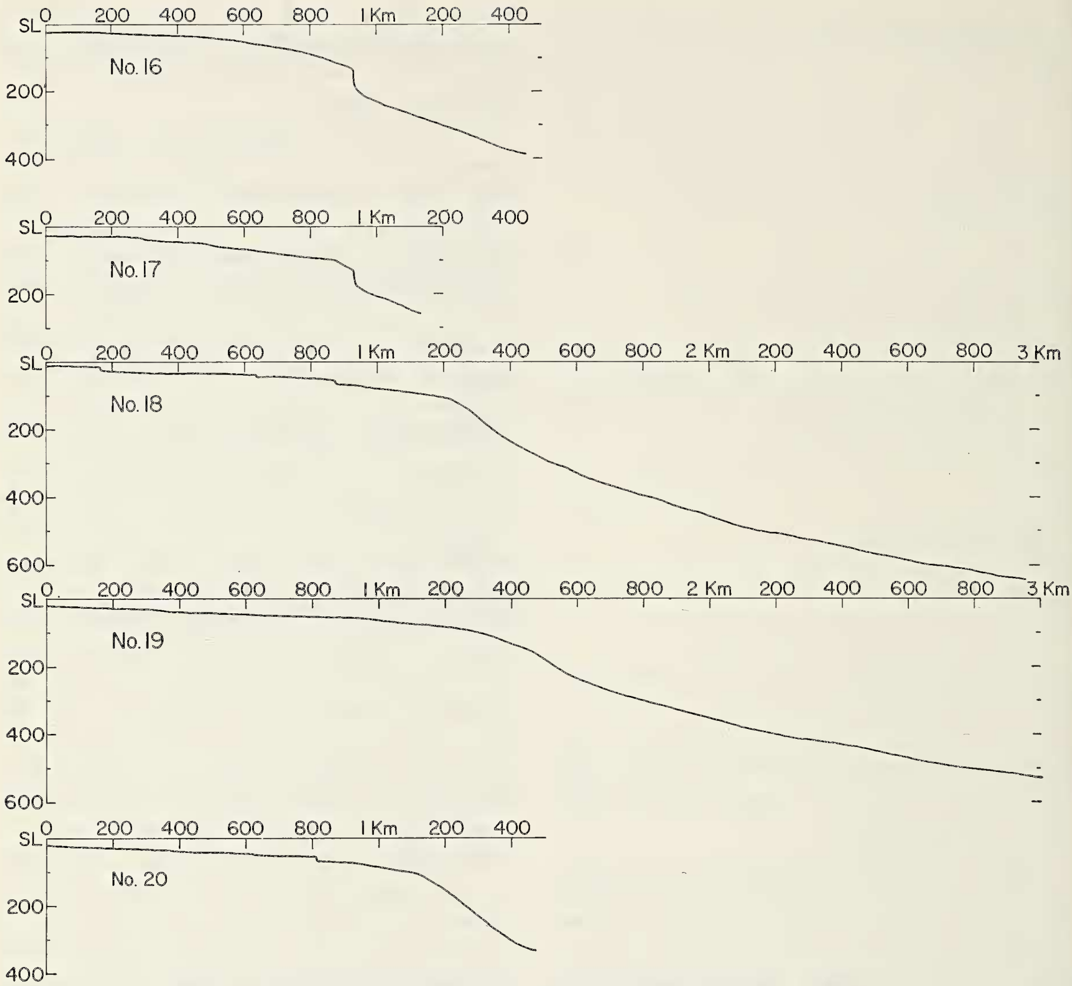

FIG. 3d. Bathymetric profiles Nos. 16–20. See Figure 1 for locations.

70 meters, but usually landward of about 75 meters another terrace level commenced, probably equated to the Penguin Banks Shelf of 55 meters depth as defined by Stearns (1966). The inner edge of this shelf was not explored with the "Asherah."

Both the Mamala and Penguin Banks shelves were very flat and, approximately south of Makua Valley, were covered extensively with patches and channels of sand. These masses of sand were generally irregular but connected into river-like masses 30 or more meters in width, which continued across the shelves and through cuts in the escarpments down to the diving limit of the "Asherah." On the Mamala and Penguin Banks shelves, the sand channels and sand patches were rippled; generally the ripples were elongated normal to the channel axis irrespective of the meandering of the channel. Usually the sand bodies were not below the general level of the shelves, except where the sand bodies passed through the various escarpments.

Lithology

Due to the limitations of the "Asherah" it was not possible to collect rock samples at the time visual observations were made. Nor was it possible to use heavy rock dredging gear aboard the "Teritu." Consequently, an adequate lithologic sampling program could not be undertaken.

Nevertheless, rock samples were dredged

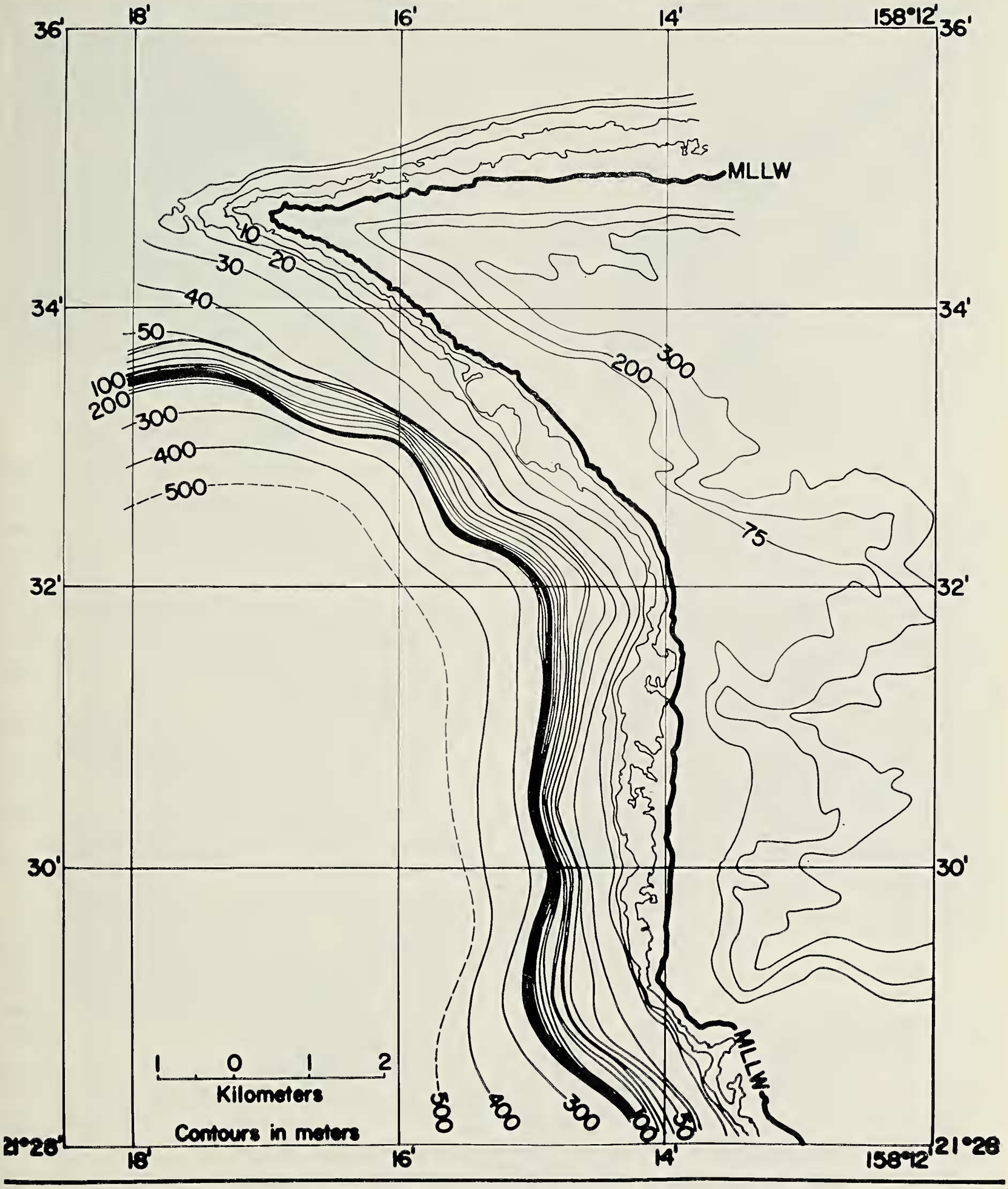

Fig. 4. Bathymetric chart of area just north of Makua Valley.

from the escarpment between the Penguin Banks and Mamala shelves. These samples were all well indurated reef limestone. No basaltic cobbles nor pebble-size fragments nor basaltic outcrops were seen on the Penguin Banks or Mamala shelves.

The rounded boulders observed at the base of the escarpment between the Lualualei and Mamala shelves and the escarpment itself appeared to be basalt, though no samples were taken of either. Fragments of basalt were numerous in the channels cutting through this

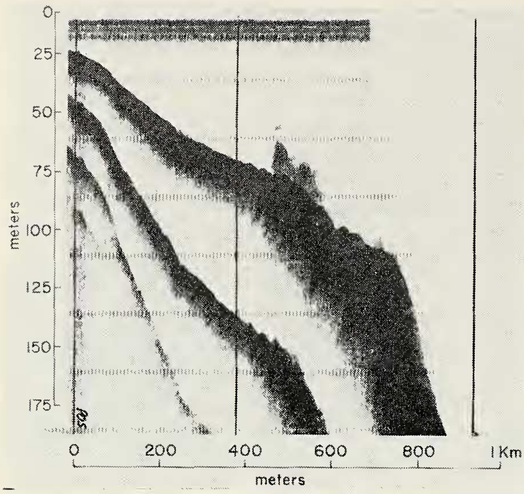

FIG. 5. Fathometer record No. 4.

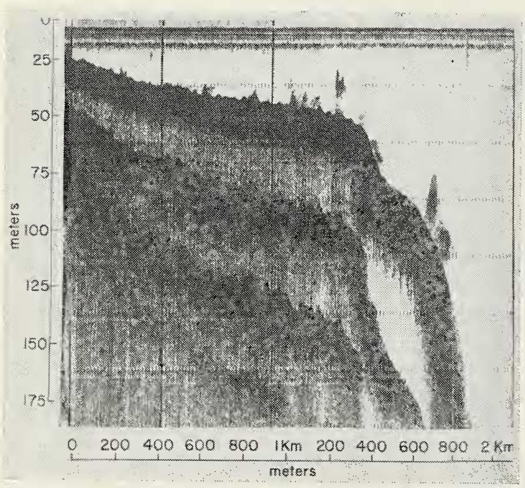

FIG. 6. Fathometer record No. 10.

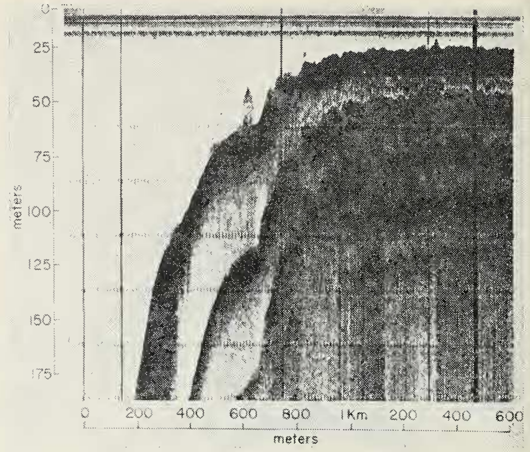

FIG. 7. Fathometer record No. 11.

escarpment and on the talus-like slopes on the inner edge of the Lualualei Shelf.

Nearshore and Offshore Sedimentation

Generally the coastal area between Kaena and Kepuhi points (herein called the Makua Cell) is one littoral unit or cell, that is, a zone in which the beaches are essentially in equilibrium, and the sand produced within or transported into the cell is just balanced by the sand lost to deep water sedimentation (Chamberlain, in press). Very little sand is transported around either Kaena or Kepuhi points.

The sand, nearshore and on the beach, is continually shifting in response to the wave and current regime, both on and offshore and alongshore. But usually there is a net, yearly, alongshore transport of sand to the south under the influence of the North Pacific Swell—high, powerful waves arising from the northwest gradient more than one-half of the time. These are mainly winter waves, and consequently most of the southward transport of sand takes place during that season.

As a result of these littoral processes, the sand-size particles, produced on the reef or carried onto the beaches from the hinterland by the intermittent streams of the area, are carried southward in the littoral cell and piled up on the southernmost beaches, and offshore against the northern side of Kepuhi Point.

The dives in the "Asherah" revealed that by no means all of the nearshore sand moves within the surf zone and on the beach to the south, but rather, a very substantial amount moves directly offshore, across the various marine terraces and escarpments into deep water. In Figure 2 an attempt is made to indicate these patches and channels by which sand is moved directly offshore.

The sand-size particles that make up the beaches, and the nearshore and offshore sand bodies between Kaena and Kepuhi points are of various composition and from various sources. Generally the sand is of medium grain-size and well sorted. Most of the constituents are remains of reef organisms; a small percentage of lithogenic components are present in the form of crystal grains of olivine and

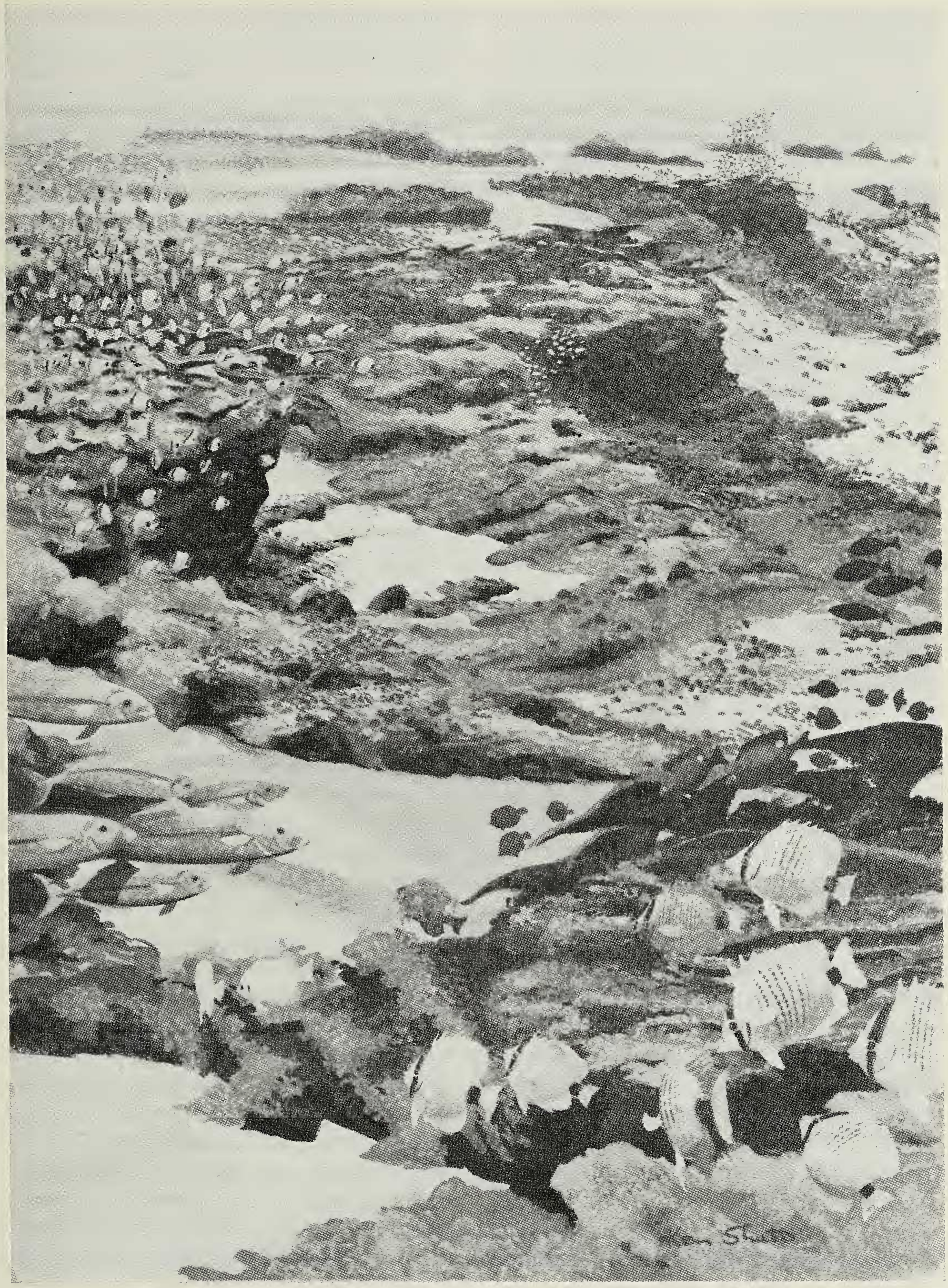

FIG. 8. Mamala Terrace at 100 meters. Shown are reef rock outcrops, the terrace, and some of the commoner fishes. (Drawing by Ken Shutt.)

weathered basalt fragments. Samples from the area of Keawaula Beach have shown the organic constituents to be mainly the remains of benthic Foraminifera, with lesser amounts of fragments of Mollusca and calcareous algae; various amounts of coral and echinoid debris are also present (Moberly and Chamberlain, 1964:137). A general discussion of the constituents of

Hawaiian beach sands can be found in the report by Moberly et al. (1965).

As can be seen from the composition, most of the sand-size particles are produced in the nearshore zone by disintegration of reef-associated organisms. Their route of transportation is unknown but probably complex. Some of the particles move onto the beaches and, as the beaches are eroded and accreted during the year, the particles migrate onshore and offshore, but year after year they are set in the direction of net alongshore transport, that is, to the south. Just north of Kepuhi Point, thick, extensive sand deposits attest to this southerly migration. During periods of intense northwesterly waves, strong littoral currents deflected seaward by Kepuhi Point as they flow southward, probably carry large quantities of this material nearshore and offshore, where it completely buries the various offshore terraces and escarpments at least down to 180 meters, the diving limitation of the "Asherah." A similar littoral cell a few miles to the south (Kahe) has been well studied and shows a similar nearshore sand circulatory pattern (Chamberlain and Marine Advisers, 1964).

The masses of sand lying on the Penguin Banks and Mamala shelves, and the accumulations of calcareous sand on the inner edges of the Lualualei Shelf at the base of the deeper escarpment must be explained in a somewhat different manner. It is quite possible that little of this sand has ever been on the beaches. Most of it, except that in the larger channels connected to the nearshore zone, is probably produced *in situ* on the deeper terraces, and by some process, yet unclear, it progresses seaward across the shelves, eventually spilling down onto the Lualualei Shelf. The larger sand channels on the deeper terraces may well be located relative to strong, offshore currents that develop within the Makua Cell during periods of storm. But most of the sand observed from the "Asherah" is moving slowly downslope under the influence of gravity, disturbed occasionally by the orbital velocity of large waves in the unidirectional flow of periodic bottom currents. Where the escarpments are very steep, for example, between the Mamala and Lualualei shelves, the calcareous sand simply spills over the escarpment edge and falls down upon various ledges and finally upon the inner edge of the Lualualei Shelf.

The quantity of sand within the Makua Cell has been estimated previously at approximately 5×10^5 cu yd (Chamberlain, in press). However, in light of the observations made from the "Asherah," this estimate is probably too low by a factor of two, perhaps even by an order of magnitude. Assuming this amount (say, 10^6 cu yd) to be a sand reservoir essentially in equilibrium with the present geologic and oceanographic conditions, then the yearly addition of new sand to this reservoir must be balanced by the yearly loss of sand from the reservoir. The yearly production or input of sand-size particles per length of coast along western Oahu is not known, but from the analyses made just to the south at Kahe, the total yearly production, or introduction, of sand into the Makua Cell is probably less than 10,000 cu yd. Nevertheless, since the principal loss of sand from the Makua Cell is to deep water sedimentation, this figure means that approximately 10,000 cu yd of sand are deposited yearly onto the inner portions of the Lualualei Shelf. The distance that this sedimentation extended out onto the Lualualei Shelf could not be ascertained from the "Asherah" due to depth restrictions, but sand-size particles were photographed on the shelf down to below 600 meters.

BENTHIC ECOLOGY AND FISH COMMUNITIES

Information on the kinds, distributions, and associations of organisms were obtained through four more or less complementary investigations: (1) by dredging and trawling, (2) by precision echo sounding, (3) by submarine photography with an automatic camera system, (4) direct observations from a research submarine.

The submarine was limited to depths of 180 meters or less and, while the other methods of investigation were not thus limited, the discussions concern observations from about 180 meters to about 25 meters. Few observations were made in water shallower than this. The nature of the bottom and its topography is described in detail in the section on geomorphology. Considered as an environment the area comprised two major biotopes: terraces, generally sand covered, and rocky areas, either outcrops of reef rock or near-vertical rocky escarpments separating the terraces. Of the latter, the important ones were a line of outcrops and low escarpments at 70 meters and massive escarpments with crests at 120 meters or deeper, paralleling the coast. Associated with the rocky areas were an abundance of fishes and in places a rich epifauna also.

The Communities of the Rocky Areas

Figures 5, 6, and 7, reproducing the actual sounding traces of the bottom, also show, more faintly and somewhat separated from the bottom, traces of what were subsequently demonstrated to be concentrations of fish. These were located generally at or above escarpment crests or over outcrops of reef rock. These concentrations of fish were investigated by cruising in the "Asherah" near the sea floor, along and across the escarpments near where the soundings were made. In addition, photographic transects were made both obliquely to the trend of the coast and at a right angle. These ran from shallow to deep water in order to minimize direct contact of the camera system with the bottom.

The visual observations made from the "Asherah" provided a dramatic contrast to the photographic ones obtained with the automatic camera system. Visual observations confirmed the indication given by the echo sounding record in finding major, but highly discontinuous, concentrations of fish associated with the escarpment crests. This was not true of the photographic transects. Fish were photographed on only a few frames of the hundreds exposed, and those photographed were species that commonly rest on the bottom or swim very near the bottom. The greatest number of fish were photographed in a few instances when the camera system was in contact with the bottom, being dragged along so that photographs were taken parallel with the sea floor.

Observations from the "Asherah" on the relative abundance of some species, suggested that the fish community associated with outcrops of reef rock at about 70 meters differed from that associated with the deeper escarpment crests further offshore at depths of 120 meters or more. The damsel fish *Chromis verater* appeared to be the most abundant species about the outcrops of reef rock. The little bass *Caesioperca thompsoni* was common in small loose schools on the face of these outcrops. *Heniochus acuminatus* was also common, frequently as individuals, but sometimes in small groups. The surmullet *Parupeneus bifasciatus* was also common near the basal portion of the outcrops or around rocks in the vicinity, but not in schools.

The angel fish *Holocanthus arcuatus* was observed as scattered individuals over rocky areas, usually very close to the bottom. The most abundant butterfly fish observed was *Chaetodon miliaris;* however this species was less numerous than the damsel fish *Chromis verater* in the rocky outcrop environment. See Figure 8.

Both *Naso hexacanthus* and *Seriola dumerilli* were observed in schools at both the outcrops of reef rock and the escarpments. The schools of *Naso* appeared to be smaller and more open in the shallower water. *Naso* schools above the crest of the deep escarpments, near large aggregations of *Chaetodon miliaris,* had the following characteristics. The schools were roughly spherical, about 3 to 7 meters across, and moved slowly between 5 and 15 meters off the bottom. The individual fish appeared to be 35 to 70 cm in length and swam rather closely together.

Seriola dumerilli were observed in roving schools of a few dozen fish. Individual fish in the schools were estimated to be larger than 70 cm and less than 150 cm in length.

Mention has been made of aggregations of *Chaetodon miliaris* above the crests of the escarpments. These occurred over a relatively small area of bottom, usually less than 50 meters across, which was somewhat elevated (by 5 meters or less) above the general height of the escarpment crest. The aggregation, or school, extended upward into the water column from 15 to 40 meters. Individual fish were 12 to 25 cm in length and appeared to be separated by distances of 0.5 to 2 meters or more apart. The fish were close to the bottom but confined to the rocky elevated portions. They did not occur down over the face of the escarpments and the diameter of the aggregation appeared to be less with increased distance from the bottom. The individual fish were in easy motion, both vertically and horizontally, but the aggregation as a whole appeared to be fixed over a specific area of the bottom. It is this feature which suggests that the large number of fish be considered an aggregation rather than a school. See Figures 5, 6, 7, 8, 9, and 10.

The schools of *Naso hexacanthus* also appeared to be oriented with respect to the aggregation of *Chaetodon miliaris* but not nearly as tightly as the latter appeared to be oriented to the sea floor topography. The *Naso hexacanthus* schools were located peripherally to the aggregation of *Chaetodon miliaris* and over the terrace rather than beyond the face of the escarpments. However, schools of the deep water snapper *Etelis carbunculus* did occur peripherally in relation to the *Chaetodon miliaris* aggregation at the level of the terrace, or deeper in open water beyond the escarpments. This species was not observed in shallower water, but it was also observed near the crest of the escarpments or beyond in deeper water where no aggregations of *Chaetodon miliaris* occurred.

These aggregations did not occur continuously along the crests of the escarpments, but appeared to occur wherever an elevated rocky area broke

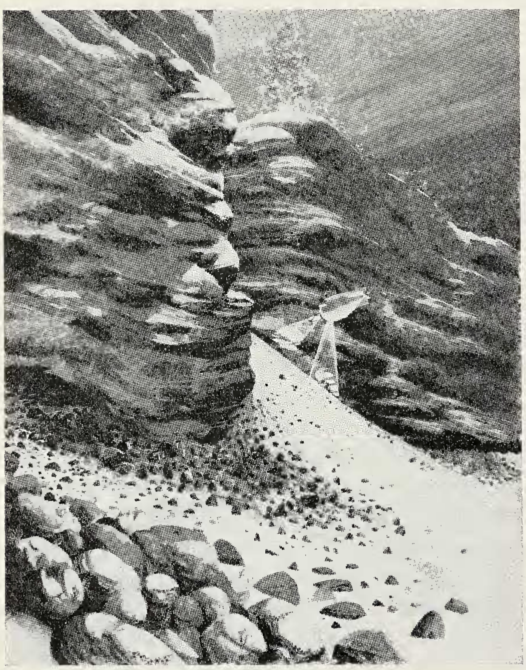

FIG. 9. Escarpment between the Mamala and Lualualei terraces at 200 meters. The "Asherah" is shown off the face of the escarpment and a fish aggregation above the crest. (Drawing by Ken Shutt.)

the crest profile. While the face of the outcrops of reef rock had had an abundant population of fish, there was a scant population along the face of the escarpments. The commonest species was an unidentified priacanthid-like fish that appeared to dwell in shallow holes on the face of the escarpments at distances of 10 meters or more apart. Small carangids were occasionally observed at all depths studied on or beyond the face of the escarpments. There were cavities of various sizes in the rocky areas. Those of apparent depth were usually thickly crowded by myripristids and holocentrids. *Holocentrus scythrops* or a species very much like it appears to be common. Spiny lobsters were also common and, while no certain identification of the species was made, *Panulirus japonicus* would at least be anticipated to occur since it appears to be commoner in deeper water within the range of SCUBA. Spiny lobsters were sighted in depths greater than 140 meters. A large moray eel, resembling *Gymnothorax flavimarginatus,* was seen at a depth of 150 meters adjacent to a cavity in the rock.

The Terrace Community

For the most part the terraces were covered by sand with little apparent epifauna. Fish were also largely absent. A large school of kawakawa (*Euthynnus yaito*) was observed, apparently foraging over a rubble- and sand-covered area about 150 meters deep. The fish were very near the bottom, less than a meter above it. Rays, probably *Dasyatis hawaiiensis* and certainly *Aetobatus narinari,* were not infrequently sighted on or over sandy areas. A very large *Dasyatis hawaiiensis* was taken in a small trawl at a depth of less than 50 meters off Pokai Bay from a sand bottom, and dredging at between 150 and 75 meters largely in sand north of Kepuhi Point resulted in an abundant catch of the heart urchin *Brissus latecarinatus* and many fragments of shells from the hatchet clam *Pinna muricata.* While the heart urchin is normally buried in the sand and is therefore not detectable visually, very extensive beds of the clam were observed from the "Asherah" and by submarine photographic transects off western Oahu and elsewhere in depths between 35 and 100 meters. One such clam bed observed from the "Asherah" was at least 500 meters across.

Subsequently, a bed which had an extent of more than 1500 meters was photographed during a submarine camera transect in an area between Maui and Lanai at a depth of 70 to 80 meters. As is characteristic for this genus, the clams were buried deeply in the substrate with the lip of the shell protruding. Individual clams were close together, appearing to be almost in contact.

The Neritic Community

Observations of the biota thus far have concerned benthic organisms, and suggest that distributions of fish are related to bottom topography. Very few fish were observed high above the bottom. However, concentrations of plankton and particulate matter, possibly organic, were observed from the "Asherah" well above the bottom and also near it, at depths of 70 to 100 meters. It was assumed that these concentrations, causing a substantially reduced visual range, were located at the bottom of the mixed layer, at the thermocline. Temperature measurements were not taken to confirm this assumption.

Discussion

The ecological observations from the "Asherah" together with the data obtained by echo sounding, submarine photography with automatic cameras, and trawling and dredging suggest the existence of two major biotopes—the terraces, and the rocky outcrops and escarpments—and that each of these contains two recognizable subdivisions. For the terrace biotope these are: (1) the sand-covered flats, and (2) the extensive beds of *Pinna muricata,* which could be better characterized as a biocoenosis. Its investigation would likely be rewarding.

The biotope of rocky outcrops and escarpment includes two subdivisions—the outcrops of reef rock characterized by *Chromis verater* and the less abundant *Caesioperca thompsoni,* and the escarpments characterized by large aggregations of *Chaetodon miliaris* and small schools of *Etelis carbunculus,* as well as other species. The observed patterns of distribution are difficult to understand in detail, but two general hypotheses are proposed, in part to provide a basis for future investigations of these matters. One hypothesis concerns the bathymetric distribution of *Pinna muricata,* and the other, the aggregations of *Chaetodon miliaris* and associated species.

Occasional specimens of *Pinna muricata* are found in quite shallow water, essentially just below the low tide level. The shallowest beds observed from the "Asherah" were about 38 meters deep, and SCUBA divers have reported beds as shallow as 25 meters. The deepest beds observed from the "Asherah" off western Oahu were at about 100 meters. This may not, of course, represent the downward extension of the range of this species. As shown in Table 1 the average temperature to and including depths of 100 meters is from 24.6° to 22.3°C, with a low temperature of 20.0°C at 100 meters. At 200 meters the average temperature is 16.7°C with a range of plus or minus 4.7°C. This is the maximum range for the water column. The temperature variation is less in either shallower or deeper water, becoming markedly less for depths in excess of 500 meters. There may be an association between the depths of abundant occurrence of *Pinna muricata* and the lower part of the mixed layer. *Pinna* is a filter feeder, and the lower part of the mixed layer may have a higher concentration of organic particulate material since such material, unless mobile, tends to settle. The sinking rate would decrease at the bottom of the mixed layer because of an increase in density of the water. As mentioned earlier a marked reduction in visual range was sometimes noted at depths between 70 and 100 meters. Upon going deeper the transparency of the water increased abruptly, with a change in visual range from 10–15 meters to 40 meters or more. If the lowest portion of the mixed layer did have a higher concentration of particulate food, the bathymetric range through which it passed may be the bathymetric range of the clam beds, with a possible additional qualification that the decrease in temperature with depth may establish an independent lower limit to the distribution of the clam.

The striking aggregations of *Chaetodon miliaris* observed over certain topographic features of the deep escarpment must relate to some essential advantage that this behavior provides in this locality. *Chaetodon miliaris* is the commonest butterfly fish in Hawaiian waters and was considered to be a coral reef fish. Its abundant occurrence in depths of 120 meters

FIG. 10. An aggregation of fish at 140 meters. A close view of a fish aggregation similar to that in Figure 9. (Drawing by Ken Shutt.)

and more was surprising. However, with the exception of *Etelis carbunculus, Caesioperca thompsoni, Chaetodon tinkeri* and possibly *Holocentrus scythrops* and one or two others, the list of fish species observed from the "Asherah" (see Table 2) are common either in nearshore reef environments or in near-surface waters. With a few additions, the fish fauna at depths to 180 meters was essentially a selected portion of a nearshore reef fish fauna.

Many of the species of fish listed in Table 2 are normally found about rocky areas in shallow

TABLE 2

A LIST OF SPECIES OF FISH OBSERVED FROM THE "ASHERAH"

SPECIES	ABUNDANCE	REMARKS
Dasyatis hawaiiensis	sighted occasionally	Over or on sand bottom.
Aetobatus narinari	sighted occasionally	Over or on sand bottom.
Gymnothorax flavimarginatus	not common	Living in holes. Other species probably present but not identified.
Holocentrus spp.	common	Living in or adjacent to cavities in rock. *H. scythrops* may be an abundant species.
Myripristis spp.	common	Habits similar to *Holocentrus*.
Caesioperca thompsoni	common	More abundant on nearshore escarpment face in small loose schools.
Apogon or *Holocentrus* spp.	dominant	Large schools of small reddish fishes (4–5 cm). Very abundant near bottom.
Seriola dumerilii	abundant	In medium-sized schools, usually in motion.
Carangids	common	Both scattered fish and small schools observed as deep as 180 meters. More than a single species involved. Not obviously part of the escarpment community.
Etelis carbunculus	abundant	In small scattered schools of 10–30 fishes frequently over deep water beyond top of outer escarpment.
Mulloidichthys pflugeri	not common	
Parupeneus bifasciatus	common	Seen more frequently about inner escarpments. Not obviously a part of the escarpment community.
Holocanthus arcuatus	common	Scattered over rocks near bottom.
Heniochus acuminatus	common	Usually seen individually or in small groups somewhat further from bottom than *Holocanthus arcuatus*.
Chaetodon tinkeri	rare	A rare deepwater Hawaiian endemic butterfly fish known heretofore only from single type.
Chaetodon miliaris	dominant	An indicator species for the escarpment community.
Chromis verater	abundant to dominant	Most abundant about nearshore escarpments. Near rocks, not high in water column.
Naso hexacanthus	dominant	In large- to medium-sized schools frequently well off bottom.
Euthynnus yaito	sighted occasionally	Few large schools observed feeding over submerged beach terrace. Not part of escarpment community.
Canthigaster cinctus	rare	Few sighted near bottom.

water and apparently find both shelter and food in a rocky environment. *Chaetodon miliaris* is such a species in nearshore areas. It is possible that *Chaetodon miliaris* occurs in major aggregations well off the bottom in the deepwater environment as a response to a plankton feeding regime. Isaacs and Schwartzlose (1965) suggested that vertically migrating zooplankton are swept over shoal areas such as banks during the night when they move upward in the water column, and then are trapped against the bottom on their downward migration with the approach of day. They may be thereby especially vulnerable to predation by fishes. A mechanism of this nature would not, however, explain the highly discontinuous distribution of fish laterally along the crest of the escarpments. It is also difficult to see what advantages would accrue through aggregating upwards of 40 meters above the bottom, in some instances over a rocky area not more than 5 meters above the average height of the escarpment crest.

Aggregations of fish do occur over rocky mounds on a much smaller scale in shallower water. Immature *Dascyllus albisella* do this over individual coral heads and seek concealment in the branches of the coral when alarmed. However, it is unlikely that the very large aggregations of *Chaetodon miliaris* use for shelter the features of bottom topography above which they aggregate. This statement would also apply to *Chromis verater.*

Fish concentrations on or over banks and in the vicinity of oceanic islands have long been noted by fishermen. Tuna fishermen in the eastern tropical Pacific have found concentrations of tuna in the vicinity of offshore banks regularly enough to make such topographic features of special interest (Bennett and Schaefer, 1965).

Four hypotheses have been offered to explain the apparent greater abundance of marine life about such topographic features, three of which would apply to banks as well as islands. The margins of continents, under many circumstances, would have similar effects on the abundance of marine life. The four hypotheses, which are not mutually exclusive, are as follows: (a) nutrients from land runoff (Gran, 1931); (b) vertical movement of water transporting nutrients into the euphotic zone (Moore, 1949); (c) increased productivity through the growth of benthic algae in relatively shallow depths (Sargent and Austin, 1949); (d) the trapping of deep scattering layer organisms (Isaacs and Schwartzlose, 1965).

A discussion of the first three of these possible mechanisms, which involve means by which the primary production is increased, is presented by Jones (1962) in connection with the discovery of larger standing crops of zooplankton as the Marquesas Islands are approached.

The pattern of fish concentrations as observed off western Oahu seem to accord best with a food resource which may be provided by the trapping of deep scattering layer organisms as suggested by Isaacs and Schwartzlose (1965). However, if this is the correct hypothesis, the observed relation among topographical features, fish concentrations, and deep scatters is a complex one, and is affected by elements that are not obvious.

CONCLUSIONS

1. At least three well-defined terraces were discernible from the "Asherah" (Fig. 1): (a) the Lualualei Terrace deeper than 180 meters, (b) the Mamala Terrace at depths of 70 to 120 meters, and (c) the Penguin Banks Terrace shoaler than 70 meters.

2. Vertical and near-vertical rock escarpments separate the Mamala Terrace from the Lualualei Terrace. In many places these escarpments were over 35 meters high and north of Makua Valley there were areas of rounded boulders at their bases; in some areas caves were present (Fig. 9). Between the Penguin Banks Terrace and the Mamala Terrace a broken line of reef rock outcrops extended up above the level of the terraces. These outcrops were from 5 to 10 meters in height and generally aligned parallel to the shore (Fig. 8).

3. Associated with these bottom structures were communities of the benthic biota. There appeared to be two major biotopes, the terraces and the rocky outcrops and escarpments. Each of these biotopes was separable into two portions based on the presence or absence of dominant species.

The terraces were largely sand covered, rather barren of fishes or obvious benthic fauna except for extensive beds of a hatchet clam *Pinna muricata,* which were both extensive enough and dense enough to constitute a biocoenosis.

The escarpments lying between the Lualualei Terrace and the Mamala Terrace had at irregular intervals large concentrations of fish associated with features of the crest. Concentrations of fish were also observed with the reef rock outcrops between the Mamala Terrace and the Penguin Banks Terrace. These concentrations appeared to differ significantly in both dominant species and the proportions of other species.

4. The majority of the species of fish and those most abundant within the range of depths observed from the "Asherah" were species common or abundant in shallow water.

5. Offshore transport of calcareous sand was evident to the diving limit of the "Asherah" (180 meters). On the Mamala and shoaler shelves, large sand "channels" and interconnected sand patches were present (Figs. 1 and

3). Seaward these sand channels spilled over the Lualualei escarpment or through gullies in that escarpment down into the Lualualei Terrace. In most places the inner edge of the Lualualei Terrace was buried with thick masses of nearshore calcareous sand mixed with escarpment talus of pebble and cobble size (Fig. 9).

6. The amount of offshore sand increased markedly from north to south; near Kepuhi Point all of the escarpments and terraces were completely buried and a single sand slope of about 5° extended from 25 meters to the depth limit of the "Asherah."

APPENDIX
EQUIPMENT SPECIFICATIONS

"Asherah"

The research submarine "Asherah" was leased from the Electric Boat Division of General Dynamics for a period of one week. Accompanying the submarine was a 3-man operating and maintenance crew and equipment to keep all systems functioning. She was 17 feet long with a spherical pressure hull 5 feet in diameter at the anterior end attached to a cone-shaped afterpart which was floodable and housed batteries, compressed air tanks, and ballast tanks.

She was rated for a maximum depth of 600 feet and for an operating period of 10 hours. Other data include:

Crew: 2, an operator and an observer
Propulsion: 2 side-mounted, 2-hp motors
Power: 24-volt storage batteries
Life support: 48 man-hours endurance (CO_2 absorbent and compressed oxygen)
Viewports: six 5-inch minimum diameter, 90° truncated cone, 2-inch-thick plexiglass; and one 2-inch skylight of 1-inch plexiglass in hatch
Weight in air: 8,500 pounds

Through a "pinger" mounted on the hull of the submarine and a directional hydrophone on board the 13-foot power boat, the approximate position of the "Asherah" was monitored throughout a dive.

Where the nature of the diving investigation permitted, the dive was begun at its deepest point, that is at 180 meters, in order to get the submarine down into cool water as soon as possible. This was desirable since in near-surface waters the temperature inside the craft, together with 100% humidity, made her uncomfortable. For this reason, near-bottom observations were taken from deep to shallow water. Both the operator and the scientific observer aboard the vehicle used the viewports and exchanged information on their observations. In addition, a portable tape recorder was used to record what was seen; however, because of the ambient noise level, the tapes were difficult to understand on playback. Photographs in monochrome and color were taken through the viewports with cameras impervious to moisture such as the Nikonos. While the "Asherah" had an external automatic camera, this was in operating condition for only a few of the dives near the termination of the program. While few of the photographs were of good quality, many were adequate to confirm visual observations.

Stereo-Photographic Equipment

The following photographic equipment, purchased from Edgerton, Germeshausen and Gier, Inc., 160 Brookline Avenue, Boston, was used throughout the "Asherah" diving operations: two 35-mm cameras, Model 200; light source, Model 210; and camera mount, Model 240.

A pinger system monitored by the "Teritu's" echo sounding recorder was used to record the camera's distance from the bottom. Its components consisted of a driver (Model 220), and a transducer (Model 221).

The entire camera system, including pinger, was powered by silver cell batteries.

Kodak TRI-X film was used for all black and white photography, Echtochrome MS film for all color photography.

Echo Sounding Equipment

The echo sounding equipment used aboard the "Teritu," and by means of which the bathymetric profiles were made, consisted of: GIFFT Transceiver: 800 watts peak power at 12 kilocycles, ALPINE *Precision Echo Sonic Recorder* (PESR), and BRAINCON towed "V" Fin incorporating an EDO transducer.

Geologic Dredges

The rock dredges were made of ¼-inch iron pipe, 14 inches in diameter and cut into 3-foot lengths. An iron grating was welded across one end and a 4-foot chain bridle attached to the other end. The cutting edges of the dredges were sharpened and tempered.

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